New bounds on neutrino electric millicharge from limits on neutrino magnetic moment

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Abstract

In various extensions of the Standard Model a neutrino can have nontrivial electromagnetic properties. In particular, a neutrino can be an electrically millicharged particle. The corresponding non-standard electromagnetic interactions generates additional contributions to the neutrino magnetic moment. New limit on the neutrino magnetic moment recently obtained by the GEMMA experiment on measurements of the reactor antineutrino scattering off electrons allows us to get a new upper bound on the neutrino electric millicharge $\mid q_\nu \mid < 5.8 \times 10^{-19} e_0$ that exceed most of the available in literature bounds on the neutrino millicharge. We also obtain the bound, $\mid q_\nu \mid < 6 \times 10^{-20} e_0$, from the astrophysical limit on the neutrino magnetic moment that is much stronger than all known astrophysical bounds on the millicharge.

1. Introduction

It seems quite possible that observation of a Higgs-like particle, recently announced by two LHC collaborations, with the further examination of its properties will yield in the discovery of the standard Higgs boson. This will provide a final experimental confirmation of the solid status of the Standard Model. Therefore, even now one can consider the neutrino to be the only particle that really exhibits properties beyond the Standard Model. In addition to the experimentally confirmed nonzero mass, flavour mixing and oscillations the neutrino nontrivial electromagnetic properties, once confirmed, would provide a clear indication for physics beyond the Standard Model.

Within the Standard Model neutrinos are massless and have "zeroth" electromagnetic properties. However, it is well known that in different extensions of the Standard Model a massive neutrino has non trivial electromagnetic properties (for a review of the neutrino electromagnetic properties see [1, 2]). That is why it is often claimed that neutrino electromagnetic properties open "a window to new physics" [3].

The neutrino electromagnetic interactions, in addition of being a powerful tool in exploring beyond the Standard Model frontier, can generate important effects when neutrinos

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propagate for long distances in presence of magnetic fields and media. Therefore, there are two main approaches for studying the neutrino electromagnetic properties. The first approach is based on consideration possible electromagnetic contributions to neutrino processes in extreme astrophysical environments. A detailed discussion of astrophysical option of constraining neutrino electromagnetic properties can be found in [4].

The second approach assumes high precision measurements of neutrino interaction cross section in the terrestrial laboratory experiments in which the electromagnetic interaction contributions are hoped to be observed in addition to the main contributions due to weak interactions. A review on the relevant present results on the upper bounds on the neutrino effective magnetic moment can be found in [1, 2].

Note that there are several attempts in the literature aimed to investigate new promising possibilities for providing more stringent constraints on the neutrino electromagnetic properties based on the existed experimental data on $\bar{\nu} - e$ scattering. For instance, an interesting possibility for getting more stringent bound on the neutrino magnetic moment from $\bar{\nu} - e$ scattering experiments based on the "dynamical zeros" appear in the Standard Model scattering cross section was discussed in [5]. Another possibility was discussed in [6] where it was claimed that electron binding in atoms (the "atomic ionization" effect in neutrino interactions on Ge target) can significantly increase the electromagnetic contribution to the differential cross section with respect to the free electron approximation. However, detailed considerations of the atomic ionization effect in (anti)neutrino atomic electron scattering experiments presented in [7–11] show that the effect is by far too small to have measurable consequences even in the case of the low energy threshold of 2.8 keV reached in the GEMMA experiment [12].

In this letter we discuss a new possibility, that have never discussed before, to obtain constraints on the neutrino electromagnetic properties using data from the laboratory $\bar{\nu}-e$ scattering experiments. In particular, using the recently reported [12] by the GEMMA collaboration bound on the neutrino magnetic moment, obtained from experimental measurements of the reactor antineutrino scattering off electrons, we derive the bound for the neutrino millicharge absolute value $\mid q_\nu \mid < 5.8 \times 10^{-19} e_0$, where e_0 is the absolute value of the electron charge. The obtained new bound is more stringent than most of other bounds previously discussed in literature, accept one obtained from the demand of neutrality of a neutron assuming electric charge conservation in the neutron beta decay. Note that the new bound on q_ν is obtained below on the solid base of measurements performed in the terrestrial laboratory experiment. In addition, we also obtain stronger limit, $\mid q_\nu \mid < 6 \times 10^{-20} e_0$, on the neutrino millicharge from the astrophysical bound [13] on the neutrino magnetic moment. This limit is much stronger than other known [4, 14] astrophysical limits on the neutrino millicharge. For completeness we also discuss the possibility of getting limits on the neutrino millicharge from the neutrino-electron scattering experiments (such as, for instance, the GEMMA experiment) that is based on consideration of the direct millicharge-to-charge neutrino scattering off electrons.

2. Electrically millicharged neutrino

It is a common knowledge that for a massive neutrino in the easiest generalization of the Standard Model with inclusion of the right-handed neutrino the neutrino magnetic moment is not zero. However, it is usually believed [15] that the neutrino electric charge is zero. This is often thought to be attributed to gauge invariance and anomaly cancellation constraints imposed in the Standard Model. In the Standard Model of $SU(2)_L \times U(1)_Y$ electroweak interactions it is possible to get [16–18] a general proof that neutrinos are electrically neutral. The electric charges of particles in this model are related to the $SU(2)_L$ and $U(1)_Y$ eigenvalues by the relation $Q = I_3 + \frac{Y}{2}$. In the Standard Model without right-handed neutrinos ν_R the triangle anomalies cancellation constraints (the requirement of renormalizability) lead to certain relations among particles hypercharges Y, that are enough to fix all Y, so that hypercharges, and consequently electric charges, are quantized [17, 18]. The electric charge quantization provides the particles charges to be equal integral multiples of one third the electron charge that together with the present experimental limits on particles charges gives a final proof that neutrinos are electrically neutral.

The direct calculation of the neutrino charge in the Standard Model under the assumption of a vanishing neutrino mass in different gauges and with use of different methods is presented in [19–25]. For the flavor massive Dirac neutrino the one-loop contributions to the charge, in the context of the minimal extension of the Standard Model within the general R_ξ gauge, were considered in [26, 27]. By these direct calculations within the mentioned above theoretical frameworks it is proven that at least at one-loop level approximation neutrino electric charge is gauge independent and vanish.

However, if the neutrino has a mass, the statement that a neutrino electric charge is zero is not so evident as it meets the eye. It is not entirely assured that the electric charge should be quantized (see [4, 14] and references therein). We recall here that the problem of charge quantization has been always a mystery within quantum electrodynamics [28]. The absence of an algebraic quantization of the charge eigenvalues in electrodynamics led to the proposal [29] of a possible topological explanation leading to magnetic monopoles.

The strict requirements for charge quantization may also disappear in extensions of the standard $SU(2)_L \times U(1)_Y$ electroweak interaction models if right-handed neutrinos ν_R with $Y \neq 0$ are included. In this case the uniqueness of particles hypercharges Y is lost (hypercharges are no more fixed) and in the absence of hypercharge quantization the electric charge gets "dequantized" [17, 18]. As a result, neutrinos may become electrically millicharged particles.

In general, the situation with charge quantization is different for Dirac and Majorana neutrinos. As it was shown in [16], charge dequantization for Dirac neutrinos occurs in the extended Standard Model with right-handed neutrinos ν_R and also in a wide class of models that contain an explicit $U(1)$ symmetry. On the contrary, if the neutrino is a Majorana particle, the arbitrariness of hypercharges in this kind of models is lost, leading to electric charge quantization and hence to neutrino neutrality [16].

Finally, while there are other Standard Model extensions (superstrings, GUT's etc) that provide enforcing of charge quantization, there are also models (for instance, with a

"mirror sector" [30]) that predict the existence of new particles of arbitrary mass and small (unquantized) electric charge, in which neutrino can be a millicharged particle.

The most severe experimental constraints on the electric charge of the neutrino

$$q_\nu \leq 10^{-21} e_0, \tag{1}$$

are obtained assuming electric charge conservation in neutron beta decay $n \to p + e^- + \nu_e$, from the neutrality of matter (from the measurements of the total charge $q_p + q_e$) [31] and from the neutrality of the neutron itself [32]. Constraints from direct accelerator searches, charged leptons anomalous magnetic moments, stellar astrophysics and primordial nucleosynthesis are in general less stringent [28, 33]:

$$q_\nu \leq 10^{-6} - 10^{-17} e_0. \tag{2}$$

A detailed discussion of different constraints on the neutrino electric charge can be found in [4, 14].

3. Bound on neutrino millicharge from GEMMA experiment

Consider a massive neutrino with non-zero electric millicharge q_ν that induces an additional electromagnetic interaction of the neutrino with other particles of the Standard Model. Such a neutrino behaves as an electrically charged particle with the direct neutrino-photon interactions, additional to one produced by possible neutrino non-zero magnetic moment μ_ν that is usually attributed to a massive neutrino.

If there is no special mechanism of "screening" of these new electromagnetic interactions then the neutrino will get a normal magnetic moment predicted within the Dirac theory of an electrically charged spin-$\frac{1}{2}$ particle

$$\mu_\nu^q = \frac{q_\nu}{2m_\nu} \tag{3}$$

that is proportional to the neutrino millicharge q_ν, here m_ν is the neutrino mass. This new contribution to the neutrino magnetic moment, that in fact has never been considered before in literature, should be added to the neutrino anomalous magnetic moment μ_ν^a that can be generated by the vacuum polarization loop interactions within different theoretical models beyond the Standard Model. We recall here that in the initial formulation of the Standard Model a neutrino is the massless particle and its magnetic moment is zero. Within the easiest generalization of the $SU(2)_L \times U(1)_Y$ Standard Model for a massive neutrino the contribution to the anomalous magnetic moment is produced by the $\nu - W - e$ loop diagramme.

Thus, for a millicharged massive neutrino one can expect that the magnetic moment contains two terms,

$$\mu_\nu = \mu_\nu^q + \mu_\nu^a, \tag{4}$$

where in the case of the Dirac neutrino [34]

$$\mu_\nu^a = \mu_\nu^D = \frac{e_0 G_F m_\nu}{8\sqrt{2}\pi^2} \approx 3.2 \times 10^{-19} \Big(\frac{m_\nu}{1\ eV}\Big) \mu_B \tag{5}$$

is a tiny value for any reasonable scale of m_ν consistent with the present neutrino mass limits ($\mu_B = \frac{e_0}{2m_e}$ is the Bohr magneton).

Here we recall that there is a hope of both theoretists and experimentalists that new interactions beyond the Standard Model might reasonably increase the anomalous part of the neutrino magnetic moment to the level that could be checked by new terrestrial laboratory experiments in the near future.

Note that in the considered case the neutrino magnetic moment decomposition to the normal μ_ν^q and anomalous μ_ν^a contributions is similar to the well known decomposition of the electron magnetic moment

$$\mu_e = \mu_B (1 + \frac{\mu_e^a}{\mu_B}). \tag{6}$$

In the case of the Standard Model of electroweak interactions the main contribution to the electron anomalous magnetic moment is generated by the $e - \gamma - e$ vacuum polarization interactions and to the first order of perturbation series expansion equals to $\mu_e^a = \frac{\alpha}{2\pi}\mu_B$, that is the so called Schwinger value (α is the fine structure constant).

The present $\bar{\nu} - e$ scattering experiments provide constraints on the upper bound of the neutrino magnetic moment irrespective of the nature of different contributions. Accounting for the recently published [12] by the GEMMA collaboration upper bound we get that

$$\mid \mu_\nu^q + \mu_\nu^a \mid < 2.9 \times 10^{-11} \mu_B. \tag{7}$$

From this, in the most conservative treatment, it follows that

$$\mid \mu_\nu^q \mid < 2.9 \times 10^{-11} \mu_B. \tag{8}$$

Here we exclude possibility of different beyond-standard-model effects overlapping in the neutrino magnetic moment and suppose that the dominant contribution is due to the neutrino millicharge, $\mu_\nu^q \gg \mu_\nu^a$. Substituting (3) to (8) we arrive to the bound for the neutrino electric millicharge,

$$\mid q_\nu \mid < 2.9 \times 10^{-11} \frac{m_\nu}{m_e} e_0. \tag{9}$$

The bound on the neutrino millicharge is proportional to the neutrino to charged lepton masses ratio $\frac{m_\nu}{m_e}$. If one considers $m_\nu = m_i \sim 10^{-2}\ \ eV$ then the limit on the neutrino millicharge is

$$\mid q_\nu \mid < 5.8 \times 10^{-19} e_0. \tag{10}$$

It is expected that the new run of the GEMMA experiment will provide the probe of the neutrino magnetic moment on the level of $\sim 1 \times 10^{-11} \mu_B$ [2]. In case no indication

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for non-zero magnetic moment were observed the limit on the neutrino millicharge will be translated to

$$| q_\nu |< 2 \times 10^{-19} e_0. \tag{11}$$

The obtained new bounds on the neutrino millicharge are more stringent than most of other bounds previously discussed in literature [28, 33].

4. Conclusions

We consider possibility, provided in various extensions of the Standard Model, that a neutrino is an electrically millicharged particle. The corresponding non-standard electromagnetic interactions of such a neutrino generates the additional contribution to the neutrino magnetic moment that is proportional to the milicharge. New upper limit the neutrino magnetic moment recently obtained by the GEMMA experiment on measurements of the reactor antineutrino scattering off electrons allows us to get a new upper bound on the neutrino electric millicharge that is stronger than most of available bounds in literature. The obtained bound (10) depends on the value of the neutrino mass and will be improved with lowering of the experimental upper bound on the neutrino magnetic moment.

It is interesting to note that much stronger limit on the neutrino millicharge can be obtain from the astrophysical bound on the neutrino magnetic moment. Consider the most stringent astrophysical upper bound on the neutrino magnetic moment [13]

$$\mu_\nu^{astr} < 3 \times 10^{-12} \mu_B \tag{12}$$

obtained from the demand that nonstandard energy loss in red giant cooling are not important so that it can't delay helium ignition. Then the corresponding limit on the neutrino millicharge is

$$| q_\nu |< 6 \times 10^{-20} e_0, \tag{13}$$

that is of the same order as one obtained [31, 32] from electric charge conservation in the beta-decay and from the neutrality of a neutron. Note that the obtained new astrophysical limit on the neutrino millicharge is much stronger than other known [4, 14] astrophysical limits.

Finally, for completeness we discuss another possibility of getting limits on the neutrino millicharge from the neutrino-electron scattering experiments (such as, for instance, the GEMMA experiment) that is based on consideration of the direct millicharge-to-charge neutrino scattering off electrons. It is of certain interest to know the range of the expected limits on the neutrino millicharge that would be obtained within this scheme. To get an estimation for the expected limits on the millicharge we compare the neutrino magnetic-moment contribution to the differential cross section [35]

$$\left(\frac{d\sigma}{dT}\right)_\mu \approx \pi\alpha^2 \frac{1}{m_e^2 T} \left(\frac{\mu_\nu^q}{\mu_B}\right)^2 \tag{14}$$

with the direct neutrino millicharge-to-charge contribution to the cross section [36]

$$\left(\frac{d\sigma}{dT}\right)_{q_\mu e} \approx 2\pi\alpha\frac{1}{m_e T^2}q_\nu^2. \tag{15}$$

These two contributions to the cross section exhibit different dependence on the electron recoil energy T and the ratio of these contributions in fact gets always huge values for the whole relevant for the GEMMA experiment range of the electron recoil energies,

$$\frac{\left(\frac{d\sigma}{dT}\right)_\mu}{\left(\frac{d\sigma}{dT}\right)_{q_\mu e}} = \frac{1}{2}\frac{m_e T}{m_\nu^2} \gg 1. \tag{16}$$

Thus it follows that the GEMMA experimental data limit on the neutrino millicharge obtained from the neutrino magnetic moment interactions is much more stringent than one would be obtained from considerations of the direct millicharge-to-charge interactions.

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